Appendix E
Sample Problem

E-1. General

The site conditions shown in Figure E-1 are as follows: design wave height H is 4.20 ft, and design wave period T is 4.25 sec. A range of possible options will be considered.

E-2. Selection of Alternatives

a. Revetments. Assume that the existing slope can be regraded to a 1V on 2H slope for revetment construction. Armoring options selected from Appendix B will be riprap, quarrystone, concrete blocks, gabions, and soil cement.

b. Seawalls. Design wave conditions at this site are too mild to warrant massive seawall construction.

c. Bulkheads. Full height retention of the bank is possible using nearly all of the alternatives in Appendix D. Steel sheetpiling, H-piles and railroad ties, and gabions will be selected for comparison.

E-3. Revetment Design

a. Breaking wave criteria. Check the given wave conditions against the maximum breaker height at the site.

$$d_s = 4.91 - 1.00 = 3.91 \text{ ft}$$

$$T = 4.25 \text{ sec}$$

$$m = 0.10 \; (\textit{nearshore bottom slope})$$

$$\frac{d_s}{gT^2} = 0.0067$$

from Figure 2-2

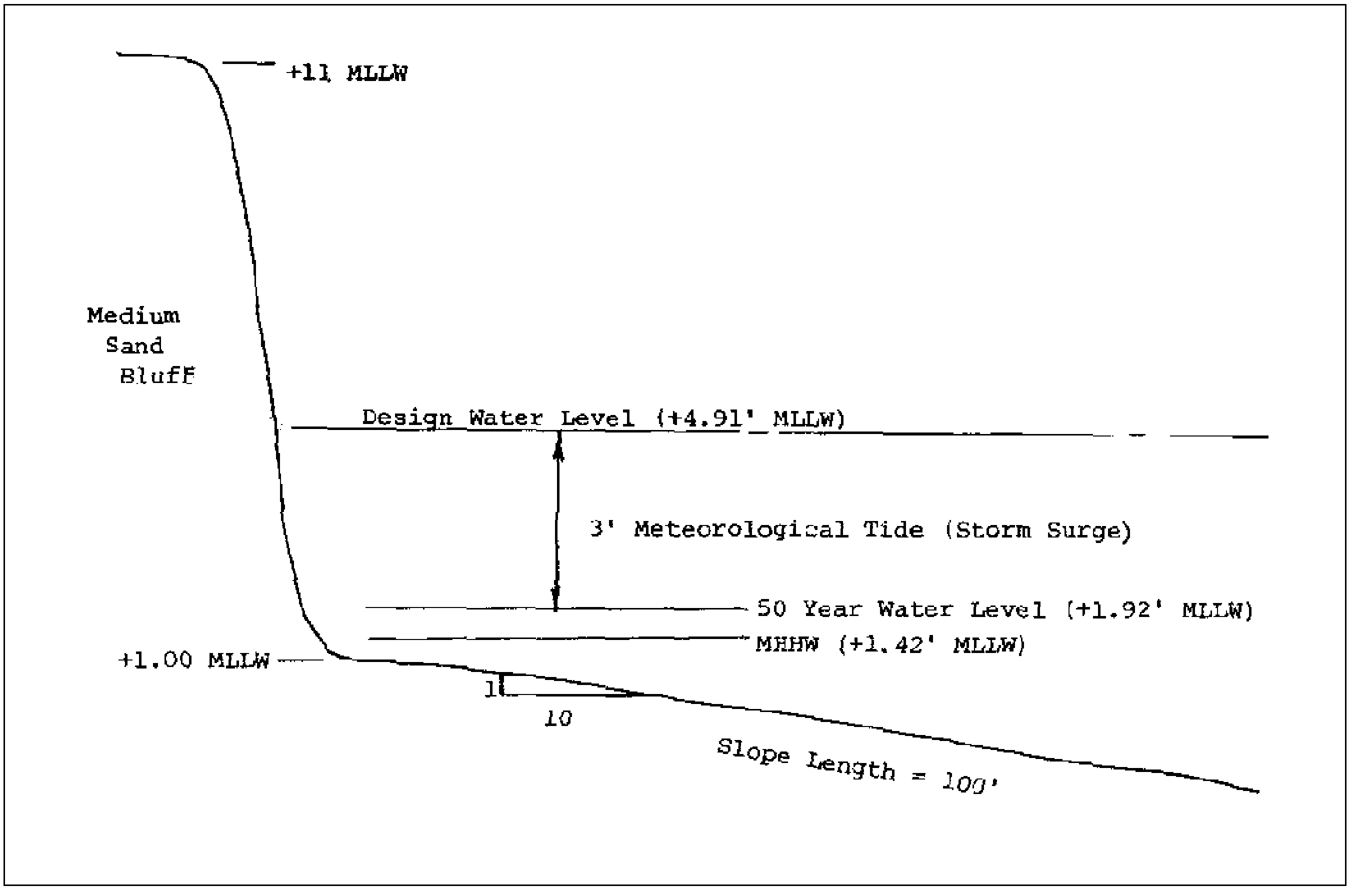

Figure E-1. Site conditions for sample problem

$$\frac{H_b}{d_s} = 1.45$$

$$\therefore\ H_b = 1.45 \times 3.91 = 5.67 \text{ ft} > 4.20 \text{ ft } (H)$$

$$\therefore\ Use\ H = 4.20 \text{ ft for design}$$

b. Armor size determination.

(1) Riprap.

$$H = 4.20 \text{ ft}$$
$$T = 4.25 \text{ sec}$$
$$\cot\theta = 2.0$$
$$\gamma_r = 165 \text{ lb/ft}^3$$
$$K_D = 2.2 \quad (\text{Table } 2.3)$$
$$\gamma_w = 64 \text{ lb/ft}^3$$

from Equation 2-15:

$$W_{50} = \frac{\gamma_r H^3}{K_D \left(\dfrac{\gamma_r}{\gamma_w} - 1\right)^3 \cot\theta}$$

$$= \frac{(165 \text{ lb/ft}^3)(4.20 \text{ ft})^3}{2.2\left(\dfrac{165 \text{ lb/ft}^3}{64 \text{ lb/ft}^3} - 1\right)^3 2.0}$$

$$= 705 \text{ lb}$$

Graded riprap this large may be difficult to obtain economically. Try rough, angular quarrystone, two layers thick ($n = 2$).

(2) Quarrystone.

$$K_D = 2.0 \quad (\text{Table } 2.3)$$

from Equation 2-15:

$$W = \frac{\gamma_r H^3}{K_D \left(\dfrac{\gamma_r}{\gamma_w} - 1\right)^3 \cot\theta}$$

$$= \frac{(165 \text{ lb/ft}^3)(4.20 \text{ ft})^3}{2.0\left(\dfrac{165 \text{ lb/ft}^3}{64 \text{ lb/ft}^3} - 1\right)^3 2.0}$$

$$= 780 \text{ lb}$$

The suggested gradation is 0.75 W to 1.25 W, or 585 lb to 975 lb with 50 percent > W (780 lb).

From Equation 2-22, the armor layer thickness r for $n = 2$ is

$$k_\Delta = 1.00 \quad (\text{Table } 2\text{-}4)$$

$$r = n k_\Delta \left(\frac{W}{\gamma_r}\right)^{1/3}$$

$$= (2)(1.00)\left(\frac{780 \text{ lb}}{165 \text{ lb/ft}^3}\right)^{1/3}$$

$$= 3.4 \text{ ft}$$

From Equation 2-23, the number of quarrystones N_r per area (use $A = 1{,}000 \text{ ft}^2$) is

$$P = 37 \text{ percent } (\text{Table } 2\text{-}4)$$

$$N_r = A n k_\Delta \left(1 - \frac{P}{100}\right)\left(\frac{\gamma_r}{W}\right)^{2/3}$$

$$= (1{,}000 \text{ ft}^2)(2)(1.00)\left(1 - \frac{37}{100}\right)\left(\frac{165 \text{ lb/ft}^3}{780 \text{ lb}}\right)^{2/3}$$

$$= 450 \text{ stones per } 1{,}000 \text{ ft}^2$$

(3) Concrete blocks. The various concrete blocks shown in Appendix B are suitable for wave heights of 4 ft and below. For some of them, however, waves larger than these are at their limit of stability. Due to the catastrophic mode of failure of such revetments, the use of a larger design wave such as H_{10} is recommended. Assuming the design wave is significant wave height H_s Equation 2-1 gives H_{10} as

$$H_{10} \approx 1.27\,H_s \approx (1.27)(4.20\ \text{ft}) \approx 5.33\ \text{ft}$$

For waves this large, mat-type units are preferred. Individually placed blocks should generally be avoided for large wave heights. However, concrete construction and concrete control blocks form a deep section that would probably be stable despite their relatively low weight/unit. Unfortunately, no reliable stability criteria exist for any of these units, and selection is purely by the judgment of the designer.

(4) Other revetment materials. Bags, filled either with sand or concrete, would probably not be stable under waves greater than 4 ft high. Gabions, laid on a slope, would have runup and overtopping values intermediate between smooth slopes and riprap; 18-in. gabions would probably be sufficient (size selected by judgment). Soil cement may be acceptable. Tire mats, landing mats, filter fabric, and concrete slabs would not be suitable due to the large wave heights.

c. Filter requirements.

(1) Quarrystone revetment. Assume that an analysis indicates that a two-stage stone filter will be required beneath the armor layer. The first underlayer will be 12 in. of crushed stone aggregates; the second layer will be 12 in. of pea gravel. A filter cloth (EOS = 70) may be substituted for the pea gravel underlayer.

(2) Block revetment. The block revetment will be underlain with a filter cloth as described above.

(3) Gabions. Assume that analysis shows that a single layer of pea gravel (12 in. thick) will be acceptable. An EOS = 70 filter cloth could also be used.

(4) Soil cement. There is no filtering requirement except that hydrostatic pressures should be relieved through regularly spaced drain pipes.

d. Wave runup estimation.

(1) Quarrystone. Assume that the design conditions given were for significant wave height and peak wave period in a depth of 15 ft. Use Equation 2-3 to find H_{mo}:

$$\frac{H_s}{H_{mo}} = \exp\left[C_0\left(\frac{d}{g\,T_p^2}\right)^{-C_1}\right]$$

$$\frac{4.20\ \text{ft}}{H_{mo}} = \exp\left[0.00089\left(\frac{15\ \text{ft}}{(32.2\ \text{ft/sec}^2)(4.25\ \text{sec})^2}\right)^{-0.834}\right]$$

$$\frac{4.20\ \text{ft}}{H_{mo}} = 1.019$$

$$H_{mo} = 4.12\ \text{ft}$$

Maximum runup is found from Equations 2-6 and 2-7:

$$\xi = \frac{\tan\theta}{\left(\dfrac{2\pi H_{mo}}{g\,T_p^2}\right)^{1/2}}$$

$$= \frac{0.5}{\left[\dfrac{(2)(\pi)(4.12\ \text{ft})}{(32.2\ \text{ft/sec}^2)(4.25\ \text{sec})^2}\right]^{1/2}}$$

$$= 2.37$$

$$\frac{R_{\max}}{H_{mo}} = \frac{a\xi}{1 + b\xi}$$

$$\frac{R_{\max}}{4.12\ \text{ft}} = \frac{(1.022)(2.37)}{1 + (0.247)(2.37)}$$

$$= 1.53$$

$$R_{\max} = (4.12\ \text{ft})(1.53)$$

$$= 6.29\ \text{ft}$$

(2) Blocks. The values shown in Table 2-2 indicate that runup will be higher for blocks than for quarrystone.

From Table 2-2, assume a value for a slope of *cot* θ *= 2.0* between the values given for *cot* θ *= 1.5* and *cot* θ *= 2.5*. The adjustment to maximum runup value is made as follows:

$$r(blocks) = 0.93$$

$$r(quarrystone) \approx 0.61$$

$$R_{max}(blocks) = R_{max}(quarrystone)$$

$$\left[\frac{r(blocks)}{r(quarrystone)}\right] = 6.29 \text{ ft}\left(\frac{0.93}{0.61}\right)$$

$$= 9.59 \text{ ft}$$

(3) Gabions. For runup on gabions, use a runup correction factor intermediate between quarrystone and blocks such a $r = 0.77$. Maximum runup is determined as above for concrete blocks:

$$r(gabions) = 0.77$$

$$r(quarrystone) \approx 0.61$$

$$R_{max}(gabions) = R_{max}(quarrystone)$$

$$\left[\frac{r(gabions)}{r(quarrystone)}\right] = 6.29 \text{ ft}\left(\frac{0.77}{0.61}\right)$$

$$= 7.69 \text{ ft}$$

(4) Soil cement. Use a riser height of 2.5 ft for a stepped slope. Runup correction factors in Table 2-2 are valid for $1 \leq H_o'/K_r$. H_o' is the deepwater wave height. Because the design H is assumed to be given in a depth of 15 ft, the wave will have shoaled from deepwater to the 15-ft depth. To determine the deepwater wave height, apply the shoaling coefficient given in Equation 2-44 of the SPM or use ACES. The wavelength for a 4.25-sec wave in a 15-ft depth is 77.56 ft (ACES or SPM Appendix C).

$$\tanh\left(\frac{2\pi d}{L}\right) = \tanh\left[\frac{2\pi(15 \text{ ft})}{77.56 \text{ ft}}\right] = 0.838$$

$$\frac{4\pi d}{L} = \frac{4\pi(15 \text{ ft})}{77.56 \text{ ft}} = 2.43$$

$$\sinh\left(\frac{4\pi d}{L}\right) = \sinh(2.43) = 5.64$$

$$\frac{H}{H_o'} = \sqrt{\frac{1}{\tanh\left(\frac{2\pi d}{L}\right)} \frac{1}{\left[1 + \frac{\left(\frac{4\pi d}{L}\right)}{\sinh\left(\frac{4\pi d}{L}\right)}\right]}}$$

$$= \sqrt{\frac{1}{0.838} \frac{1}{\left[1 + \frac{2.43}{5.64}\right]}} = 0.913$$

$$H_o' = \frac{H}{0.913} = \frac{4.20 \text{ ft}}{0.913} = 4.60 \text{ ft}$$

Using $K_r = 2.5$ ft,

$$\frac{H_o'}{K_r} = \frac{4.60 \text{ ft}}{2.5 \text{ ft}} = 1.84$$

which is within the acceptable range. Therefore, determine the maximum runup as:

$$r(vertical\ risers) = 0.75$$

$$r(quarrystone) \approx 0.61$$

$$R_{max}(vertical\ risers) = R_{max}(quarrystone)$$

$$\left[\frac{r(vertical\ risers)}{r(quarrystone)}\right] = 6.29 \text{ ft}\left(\frac{0.75}{0.61}\right)$$

$$= 7.73 \text{ ft}$$

(5) Runup summary. The required top elevation to preclude overtopping is the design water level plus the predicted runup. These values are given in Table E-1.

The top of the bank is at +11 ft mllw; therefore, overtopping should be considered. A splash apron should be provided for those alternatives, and drainage of the excess water may be necessary. Overtopping rates were covered in paragraph 2-14 and in Section 7.22 of the SPM. These rates should be determined to properly design any required drainage features, but this will not be investigated in this example.

Table E-1
Predicted Runup and Required Crest Elevations for Sample Revetment Options

Structure	Water Level, ft	Runup, ft	Crest Elevation, ft
Quarrystone	4.91	6.29	11.20 ≈ 11.25
Concrete blocks	4.91	9.59	14.50
Gabions	4.91	7.69	12.6 ≈ 12.50
Soil cement	4.91	7.73	12.64 ≈ 12.50

e. Toe scour. The toe scour depth below the natural bottom will be assumed equal to the wave height. The toe is exposed at mean lower low water (mllw). The maximum water depth is 3.91 ft at the design water level. From paragraph E-3*a*, the maximum breaker height at the design water level is 5.67 ft. The depth of toe scour should be estimated based on a wave larger than the significant design wave of 4.20 ft. In paragraph E-3*b*(3) it powas found that H_{10} = 5.33 ft. Therefore, assume that the maximum scour depth will be about 5 ft beneath the existing bottom. This is probably conservative in that it does not consider structure, shapes, or wave reflection properties. The minimum predicted scour depths are shown below in Table E-2. Rock toe protection or structure embedment will be at least the maximum depth except in the case of gabions where their flexibility will be relied on to cut off any toe scour that may occur.

f. Design summary. Design cross sections for each alternative are shown in Figure E-2. Table E-3 summarizes revetment design data.

E-4. Bulkhead Design

a. Sheetpiling. Cantilever or anchored sections are chosen based on standard structural design calculations. Important design considerations are wave runup and toe protection.

(1) Wave runup. Using SPM Figure 7-14 with

$$\frac{d_s}{H_o'} = \frac{3.91\ \text{ft}}{4.60\ \text{ft}} = 0.85$$

$$\frac{H_o'}{gT^2} = \frac{4.60\ \text{ft}}{(32.2\ \text{ft/sec}^2)(4.25\ \text{sec})^2} = 0.0079$$

read from SPM Figure 7-14

$$\frac{R}{H_o'} = 1.70$$

$$R = (H_o')(1.70) = 7.82\ \text{ft}$$

Correcting for scale effects with SPM Figure 7-13

$$R' = (1.21)(7.82\ \text{ft}) = 9.46\ \text{ft}$$

The required elevation of the top of the wall is therefore

$$4.91\ \text{ft} + 9.46\ \text{ft} = 14.37\ \text{ft mllw}$$

Table E-2
Estimated Toe Scour Depths for Sample Revetment Options

	Scour Depth, ft		
Revetment Type	Maximum	Minimum	Reflection Potential
Quarrystone	5.0	2.5	Low
Concrete blocks	5.0	2.5	Low-Moderate
Gabions	5.0	4.0	Moderate-High
Soil cement	5.0	4.0	Moderate-High

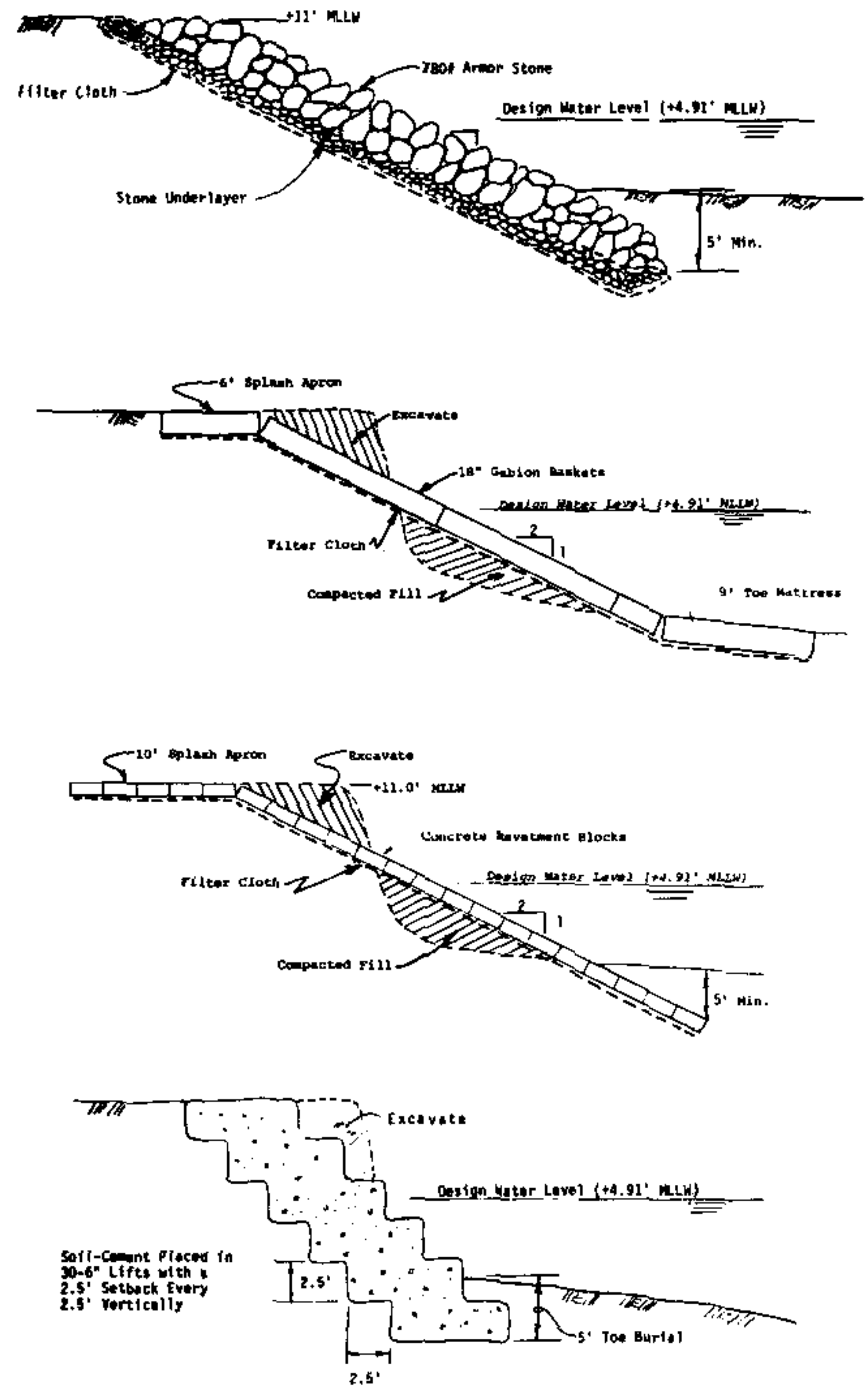

Figure E-2. Revetment section alternatives

Table E-3
Summary of Revetment Design Options

Revetment Type	Armor Size	Wave Height ft	Crest Elevation		Minimum Toe Scour ft
			Required ft	Actual ft	
Quarrystone	780 lb	4.20	11.25	11.00	2.5
Concrete blocks	Note (1)	5.30	14.50	11.00	2.5
Gabions	18-in. baskets	4.20	12.50	11.00	4.0
Soil cement	Note (2)	4.20	12.50	11.00	4.0

(1) Mats of concrete blocks will be used.
(2) Layer thickness will be 2.5 ft.

Because the height of the shoreline is only 11.0 ft mllw, overtopping will occur and a splash apron should be provided.

(2) Toe protection. Under design water level conditions the toe will be submerged. The toe stone should be sized in accordance with Equation 2-15. Use the H_{10} wave height of 5.33 ft. Note that the actual slope of the toe protection would be nearly flat. Using $\cot\theta = 3.0$ is conservative. The suggested gradation would be 0.75 *W* to 1.25 *W*, or 795 lb to 1,325 lb, with 50 percent greater than *W* (1,060 lb).

Layer thickness is determined from Equation 2-22 with $n = 2$ and $k_\Delta = 1.00$ (Table 2-4).

$$H_{10} = 5.33 \text{ ft}$$

$$\gamma_r = 165 \text{ lb/ft}^3$$

$$K_D = 2.0 \quad (\text{Table 2-3, rough, angular quarrystone})$$

$$\frac{\gamma_r}{\gamma_w} = \frac{165 \text{ lb/ft}^3}{64 \text{ lb/ft}^3} = 2.58$$

$$\cot\theta = 3.0$$

$$W = \frac{\gamma_r H^3}{K_D \left(\frac{\gamma_r}{\gamma_w} - 1\right)^3 \cot\theta}$$

$$= \frac{(165 \text{ lb/ft}^3)(5.33 \text{ ft})^3}{2.0\left(\frac{165 \text{ lb/ft}^3}{64 \text{ lb/ft}^3} - 1\right)^3 3.0}$$

$$= 1{,}060 \text{ lb}$$

$$r = n k_\Delta \left(\frac{W}{\gamma_r}\right)^{1/3}$$

$$= (2)(1.00)\left(\frac{1{,}060 \text{ lb}}{165 \text{ lb/ft}^3}\right)^{1/3}$$

$$= 3.7 \text{ ft}$$

Assume an anchored section as shown in Figure E-3. The toe apron should protect the passive earth pressure zone but should be no less than twice the wave height. The width of the passive earth pressure zone is

$$Width = K_p d_e$$

$$= (2.46)(6.5 \text{ ft}) = 16 \text{ ft}$$

which assumes a soil ϕ of 25 deg and a K_p value of 2.46. Use a 16-ft toe apron width, as this is longer than twice the wave height (5.33 ft x 2 = 10.66 ft).

b. Other bulkhead materials. Concrete slabs and king-piles are probably too expensive for all but very large installations. Railroad ties and steel H-piles are acceptable provided marine borer activity can be resisted by standard creosote-treated ties. The same is true for other timber structures. Hogwire fencing and sandbags are suitable for temporary structures, as are used rubber tires. Used concrete pipes cannot retain the full bluff height. Gabions can be stacked to almost any height needed in bluff situations. Figure E-3 contains sections of a railroad tie and H-pile bulkhead and a gabion bulkhead.

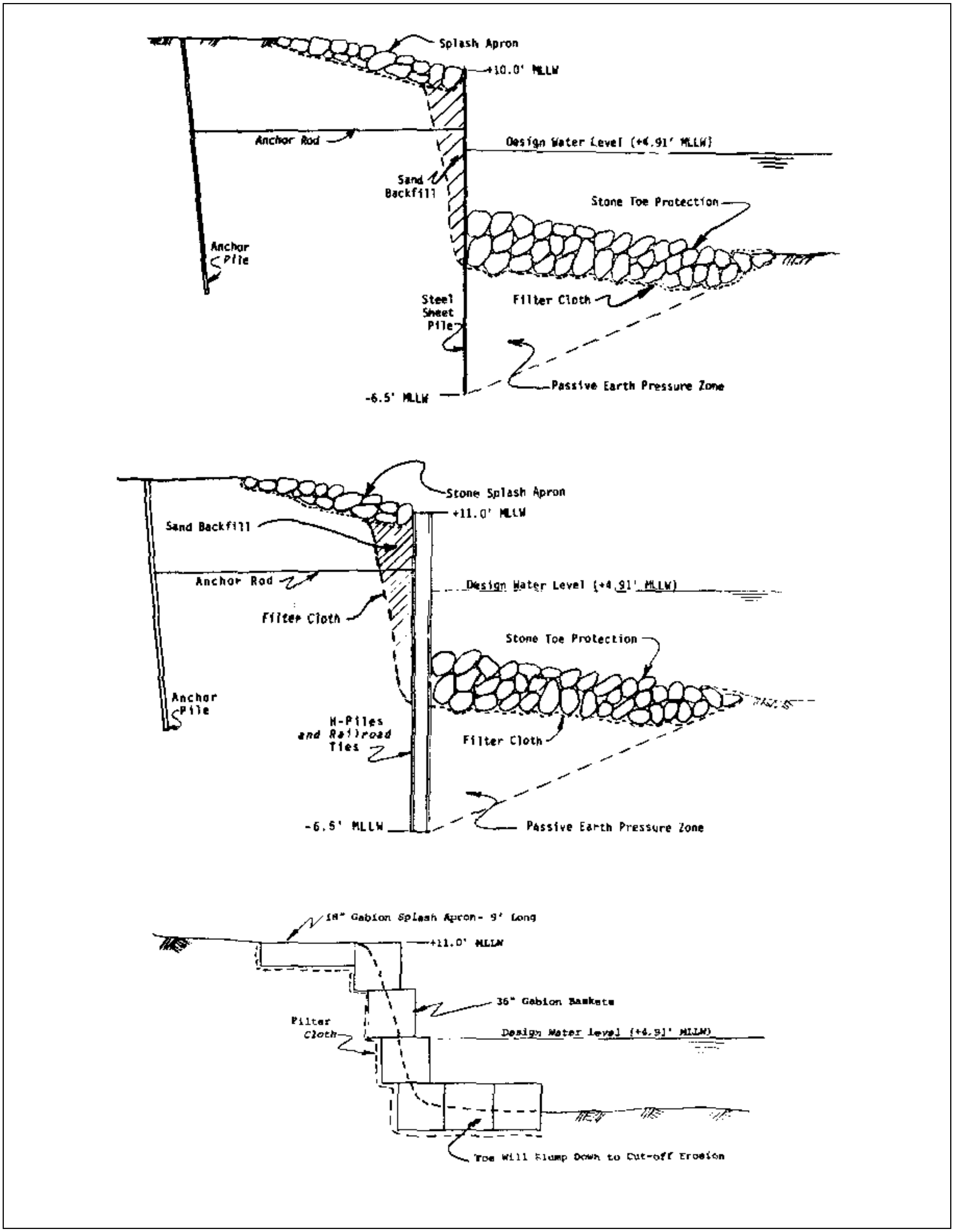

Figure E-3. Bulkhead section alternatives

Toe protection for the gabion bulkhead should extend horizontally for one wave height. Use 6 ft, which is the width of two of the 36-in. baskets shown in Figure E-3.

E-5. Cost Estimates

Cost estimates will be developed for 1,000 lin ft of protection. These estimates are shown for illustrative purposes only and should not be interpreted as definitive of costs likely to be encountered at a specific project site. Costs of various options can vary significantly in different parts of the country depending on availability of materials and transportation charges. It is likely that the relative ranking of options (based on cost) for a particular project would be entirely different from the one developed here.

a. Revetments. Assume all revetments will be placed on a 1V to 2H slope achieved by grading the bluff face. Assume the site preparation costs shown in Table E-4.

(1) Quarrystone. From paragraph E-3*b*(2), the layer thickness is 3.4 ft. The total stone volume is 4,300 yd^3 (including the embedded toe). Underlayers will be 12 in. of crushed stone over 12 in. of pea gravel or 12 in. of crushed stone over a filter cloth. Costs of these items are shown in Table E-5.

(2) Concrete blocks. Use a typical mat material that is commercially available. Place it over a filter cloth with a 10-ft-wide splash apron. Item costs are shown in Table E-6.

Table E-4
Site Preparation Costs for Revetment Alternative

Item	Quantity	Unit Cost, $	Total Cost, $
Site clearing	0.3 acre	3,000	900
Excavation	3,700 yd^3	2.25	8,325
Grading	2,500 yd^2	0.50	1,250
Total			$10,475

Table E-5
Material Costs for Armor Stone Revetment Alternative

Item	Quantity	Unit Cost, $	Total Cost, $
Armor stone	4,300 yd^3	60.00	258,000
12-in. crushed stone	3,745 yd^2	4.35	16,275
12-in. pea gravel	3,745 yd^2	2.95	11,050
Filter cloth	36,830 ft^2	0.25	9,200
Toe excavation	720 yd^3	2.25	1,625
Total using filter cloth			$285,100

(3) Gabions. Use 18-in. baskets with a 9-ft-wide toe blanket and a 6-ft-wide splash apron. Place them over a filter cloth or 12 in. of pea gravel. Material costs for this option are shown in Table E-7.

(4) Soil cement. Place in 31 6-in. lifts, with each lift being 6 ft wide. Final grading will not be required for site preparation. Material costs for this option are listed in Table E-8.

(5) Revetment summary. Table E-9 contains a summary of initial costs for the four revetment options.

Table E-6
Material Costs for Concrete Block Revetment Alternative

Item	Quantity	Unit Cost, $	Total Cost, $
Block mat	43,700 ft^2	3.25	142,025
Filter cloth	43,700 ft^2	0.25	10,925
Toe excavation	720 yd^3	2.25	1,620
Total			$154,570

Table E-7
Material Costs for Gabion Revetment Option

Item	Quantity	Unit Cost, $	Total Cost, $
Gabions	4,155 yd^2	35.00	145,425
12-in. pea gravel	4,155 yd^2	2.95	12,260
Filter cloth	37,400 ft^2	0.25	9,350
Total using filter cloth			$154,775

Table E-8
Material Costs for Soil-Cement Revetment Option

Item	Quantity	Unit Cost, $	Total Cost, $
Backfill	3,700 yd^3	1.00	3,700
Soil-cement treatment	20,665 yd^2	2.90	59,930
Compaction	3,700 yd^3	4.00	14,800
Toe excavation	1,000 yd^3	2.25	2,250
Total			$80,680

Table E-9
Summary of Initial Costs for the Revetment Options

Option	Site Preparation, $	Construction, $	Total Cost, $
Quarrystone	10,475	285,100	295,575
Concrete blocks	10,475	154,570	165,045
Gabions	10,475	154,775	165,250
Soil cement	9,225	80,680	89,905

b. Bulkheads. Assume only site clearing is required for preparation. From Table E-4, total site preparation cost is $900.

(1) Steel sheetpiling. Assume a 10-ft height plus a 6.5-ft embedded length for an anchored wall. Use 1,055-lb stones for toe protection. Material costs are listed in Table E-10.

(2) Railroad ties and steel H-piles. Use 1,055-lb stones for toe and splash protection. Material costs are listed in Table E-11.

(3) Gabions. Use 36-in. baskets with a 9-ft toe blanket and a 6-ft splash apron of 18-in. baskets. Material costs are listed in Table E-12.

(4) Bulkhead summary. Table E-13 contains a summary of initial costs for the three bulkhead options.

c. Annual costs. Compute annual costs based on a federal discount rate (7-7/8 percent for this example) and annual maintenance costs equal to the given percentage of the initial cost. All options are based on a 50-yr life. The annual costs are summarized in Table E-14.

d. Summary. Based on total annual costs, the gabion bulkhead would be most economical at this site, followed closely by the soil-cement revetment. The environmental and social impacts must also be considered before a final design is selected.

Table E-10
Material Costs for Steel Sheetpile Bulkhead Option

Item	Quantity	Unit Cost, $	Total Cost, $
Sheetpiling	16,500 ft^2	11.00	181,500
10-ft anchor piles and anchor rods	200 ft	14.00	2,800
Toe protection	2,975 yd^3	60.00	178,500
Splash apron	820 yd^3	60.00	49,200
Filter cloth	26,000 ft^2	0.25	6,500
Backfill	100 yd^3	1.00	100
Total			$418,600

Table E-11
Material Costs for Railroad Ties and Steel H-Pile Bulkhead Option

Item	Quantity	Unit Cost, $	Total Cost, $
25-ft steel H-piles	117 ea	500.00	58,500
Railroad ties	1,950 ea	40.00	78,000
Filter cloth	1,000 ft^2	0.25	250
Backfill	100 yd^3	1.00	100
Toe protection	2,975 yd^3	60.00	178,500
Splash apron	820 yd^3	60.00	49,200
Total			$364,550

Table E-12
Material Costs for Gabion Bulkhead Option

Item	Quantity	Unit Cost, $	Total Cost, $
Gabions, 36-in. baskets	2,000 yd^3	60.00	120,000
Gabions, 18-in. baskets	670 yd^2	35.00	23,450
Filter cloth	31,650 ft^2	0.25	7,925
Backfill	100 yd^3	1.00	100
Total			$151,475

Table E-13
Summary of Initial Costs for the Bulkhead Options

Option	Site Preparation, $	Construction, $	Total Cost, $
Steel sheetpiling	900	418,600	419,500
Railroad ties and steel H-piles	900	364,550	365,450
Gabions	900	151,475	152,375

Table E-14
Summary of Annual Costs for Revetment and Bulkhead Options

Option	Total Initial Cost, $	Capital Recovery Cost, $	Maintenance (Annual %)	Annual Maintenance Cost, $	Total Annual Cost, $
Revetments					
Quarrystone	295,575	23,270	1	2,955	26,225
Concrete blocks	165,045	12,910	5	8,250	21,160
Gabions	165,250	12,930	5	8,260	21,190
Soil-cement	89,905	7,030	15	13,490	20,520
Bulkheads					
Steel sheetpiling	419,500	32,820	1	4,200	37,020
Railroad ties and steel H-piles	365,450	28,590	5	18,270	46,860
Gabions	152,375	11,920	5	7,620	19,540